Characterization of the Immersion Factor for a Series of In-Water Optical Radiometers

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ABSTRACT

Spectral immersion factors, $I_f(\lambda)$, account for the difference between the in-air and in-water absolute response of submersible radiometers and are required to properly apply the in-air absolute calibration of the sensor when used underwater. The use of the so-called typical values for a series of in-water radiometers is a source of uncertainty because of intrinsic instrument-to-instrument differences in the optics. To investigate this source of uncertainty, in addition to uncertainties associated with determining the immersion factors using a laboratory method, a sample of nine radiometers from the same series of instruments was characterized by three different laboratories. A comparison of the immersion factor characterizations from the three laboratories indicates average intralaboratory measurement repeatabilities ranging from 0.3% to 0.6%, which were evaluated using multiple characterizations of the same reference radiometer and defined by two standard deviations. Interlaboratory relative uncertainties, evaluated with $I_f(\lambda)$ data from the nine sample radiometers, show average percent differences ranging from −0.5% to 0.6%. The dispersion of $I_f(\lambda)$ values across all the radiometers show values up to 5% in the red part of the spectrum with a spectral average of 2% (defined by two standard deviations). Typical $I_f(\lambda)$ values, computed with data from the so-called trusted radiometers (i.e., those not showing extreme outlier values), are also presented with their maximum uncertainties and a discussion on their spectral dependence.

1. Introduction

The absolute response of an optical instrument is different when it is used in air or in water, because of the refractive indices of the two media. In the case of an in-water radiometer designed for radiance measurements, the change in response characterizing in-air and in-water measurements is mostly due to (i) the relative difference in transmittance through the glass window located in front of the aperture and (ii) the relative change in the solid angle field of view. In the case of an in-water radiometer designed for irradiance measurements (using collectors made of a diffusing material and exhibiting a cosine angular response), the change in absolute response is primarily caused by the relative changes in the reflection properties of the air-collector and water-collector interfaces, and specifically by (i) a relative change in the reflection coefficient at the external surface of the collector (i.e., the so-called external reflection factor) and (ii) a relative change in the reflection coefficient of the internal surface of the collector (i.e., the so-called internal reflection factor).

The differences in absolute response caused by immersion effects are accounted for through spectral multiplication coefficients—the so-called immersion factors—applied to the in-air absolute radiometric calibration coefficients. The immersion factors have a value of 1 for in-air measurements and are greater than 1 (as a function of the material and geometric features of the optics) for in-water measurements. Spectral immersion factors for radiometers measuring in-water radiance are usually computed from the refractive indices of water and the glass window. Spectral immersion factors for radiometers measuring in-water irradiance need to be experimentally determined, because of the complex function relating the refractive index of water and the optical and geometrical characteristics of the collector.

a. Background

Early studies on immersion effects were carried out by Atkins and Poole (1933). They made an attempt to describe the internal and external reflection factors for an opal glass diffuser. To experimentally estimate these

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reflection contributions, they used a gas-filled lamp as a light source to vertically illuminate the diffuser when it was dry and wet, that is, in-air and in-water covered with different depths of distilled water, respectively. The authors proposed a constant immersion factor of 1.09 for opal glass diffusers to compensate for instrument sensitivity loss when operated in the water with respect to in the air. More recently, Berger (1958) presented (i) a discussion of the immersion effects in the presence of a thin layer of water producing direct reflections between the external surface of the diffuser and the water subsurface (a limiting factor in the characterization of the immersion factor) and (ii) a description of a simple method for experimentally determining the immersion factor of disk-shaped diffusers of radius r_d based on a wide blackened funnel to hold pure water above the diffuser with a water depth of at least 0.9 r_d. Notable contributions from Berger (1958) included observations and theoretical data on the immersion effects for different disk-shaped diffusers made of silicate and plastic glass showing a wide range of variations for the immersion factor.

Data from Berger (1961) were later used by Westlake (1965) to extensively describe the reflection–refraction processes occurring at the air–diffuser and at the water–diffuser interfaces in the presence of thin or deep layers of water. Westlake (1965) presented estimates of the different internal and external reflection contributions and suggested a constant immersion factor of 1.19 for opal glass, significantly higher than that proposed earlier by Atkins and Poole (1933).

A comprehensive description of a protocol for the experimental characterization of the immersion factor of in-water irradiance collectors was given by Smith (1969). The protocol, which included vertical measurements in air and in water with different depths of water above the diffuser, suggested the use of a collimated beam as a light source to avoid changes in the energy falling on the collector when different water depths were used. Smith (1969) presented a spectral characterization of the immersion factor of a cosine collector made of clear Plexiglas bonded together with translucent Plexiglas (with the latter in contact with water). The author determined immersion factors ranging within 1.34–1.22, almost linearly varying in the spectral interval 400–750 nm (as summarized in Tyler and Smith 1970), respectively, and qualitatively explained the spectral values with a dependence on the absorbance of the collector.

Petzold and Austin (1988) revised the protocol for characterizing immersion factors for irradiance collectors. They proposed using a lamp as a light source by introducing a geometric correction factor originally applied by Aas (1969) that, as a function of the lamp-collector distance, water depth, and water refractive index, minimizes effects due to changes in the energy falling on the collector as a function of a change in water depth. Applying the former method, Mueller (1995) analyzed $I_f(\lambda)$ for collectors made of Plexiglas and Teflon for several radiometers from the same manufacturer. Mueller reported $I_f(\lambda)$ values almost linearly decreasing with wavelength and ranging, on the average, within 1.38–1.32 in the spectral interval 406–670 nm, respectively.

7. Conclusions

The present study, through multiple characterizations of the same radiometer, has demonstrated the possibility of achieving a measurement repeatability that is on average better than 0.6% (expressed by 2σ) on the characterization of $I_f(\lambda)$. Interlaboratory comparisons showed relative average uncertainties to be generally less than $\pm0.6\%$ for both the reference radiometer and the multiple radiometer analyses (Tables 3 and 4). Similarly the method precision showed average values of 1.2% for both the single- (reference) and the multiple-radiometer analyses. The level of agreement between the single- and multiple-radiometer results establishes the consistency of the statistical approach (i.e., the number of characterizations was sufficient to quantify the primary analytical variables) and of the $I_f(\lambda)$ methodology (i.e., the major source of differences was associated with the water quality at each laboratory). The variability in $I_f(\lambda)$, within a sample of nine OCI-200 radiometers covering about 10% of the instrument production from 1994 to 1999, showed average dispersion values on the order of 2% with spectral values as high as 5%. An attempt at producing typical $I_f(\lambda)$ values for the OCI-200 series of radiometers showed maximum uncertainties spectrally varying from $\pm1.4\%$ to $\pm3.4\%$. This fully confirms the need, already pointed out by Mueller (1995), of ensuring a full spectral characterization of $I_f(\lambda)$values for each in-water radiometer required for an accurate absolute determination of irradiances [i.e., $E_u(z, \lambda)$, $E_d(z, \lambda)$] and derived quantities [i.e., $Q_n(z, \lambda)$, $R(z, \lambda)$].

An analysis of the sources of intra- and interlaboratory differences showed that an accuracy increase together with a standardization in $I_f(\lambda)$ characterization can be obtained by taking the following steps:

1) ensuring the best possible water purity to reduce scattering effects of particles (practical solutions may require reduction in the size of tanks to handle relatively small volumes of pure water);
2) skimming the surface to remove floating particles, which may change the surface transmittance [the alternative use of soap requires further investigation because soap slicks forming at the surface may spectrally affect the surface transmittance and thereby produce an overestimate of $I_f(\lambda)$];
3) using pure seawater instead of pure water (a practical alternative is to use pure water and apply a correction factor accounting for differences in the refractive indices between pure seawater and pure water);
4) applying quality assurance indices [like the $K(\lambda)$ values] to remove measurement sequences affected by a decreased quality of water or changes in the optical–mechanical setup;
5) using a small source and monitoring its stability during measurement sequences; and
6) minimizing the optical load of collectors by taking data at water depths larger than the radius of the area covered by the collectors.